Wave Monitoring with Wireless Sensor Networks

Mihai Marin-Perianu [1], Supriyo Chatterjea [1], Raluca Marin-Perianu [1]
Stephan Bosch [1], Stefan Dulman [2], Stuart Kininmonth [3], Paul Havinga [1]
[1] *Pervasive Systems Group, University of Twente, The Netherlands*
{m.marinperianu, s.chatterjea, r.s.marinperianu, s.bosch, p.j.m.havinga}@utwente.nl
[2] *Ambient Systems, The Netherlands*
dulman@ambient-systems.net
[3] *Australian Institute of Marine Science, Australia*
s.kininmonth@aims.gov.au

Abstract

Real-time collection of wave information is required for short and long term investigations of natural coastal processes. Current wave monitoring techniques use only point-measurements, which are practical where the bathymetry is relatively uniform. We propose a wave monitoring method that is suitable for places with varying bathymetry, such as coral reefs. Our solution uses a densely deployed wireless sensor network, which allows for a high spatial resolution and 3D monitoring and analysis of the waves. The wireless sensor nodes are equipped with low-cost, low-power, MEMS-based inertial sensing. We report on lab experiments with a Ferris wheel contraption, which is a technique used in practice to evaluate and calibrate the state-of-the-art wave monitoring solutions.

1. Introduction

Wave monitoring is an essential task in a wide variety of day-to-day activities. As an example, wave structure information is used by marine scientists, environmental protection agencies, port authorities, the fishing industry and even beach-goers such as surfers.

Since 1991, the Queensland Environmental Protection Agency (EPA) [3] has been continuously collecting and analyzing wave data, in order to help short-term and long-term investigations of natural coastal processes such as accretion and erosion. In case of a cyclone approaching the coast, the wave data is of particular importance to provide advice to the State Counter Disaster Organization on the potential impact of waves on coastal communities. Furthermore, the wave monitoring program supports maritime organizations to better plan port activities and to update navigational information.

Wave monitoring for the above-mentioned examples is commonly performed by offshore buoys such as the waverider buoy [1] or underwater pressure/acoustic sensors [2]. The waverider buoys transmit data periodically to the base-station on the shore by means of a long-distance, high-frequency wireless connection where as the underwater pressure sensors are usually connected to a data logger by means of a cable. The waverider buoys are highly accurate measurement units based on stabilized inertial platforms. They can achieve 0.5% accuracy for heave measurement and 0.4° -2° heading error. The pressure sensors are usually mounted on a tripod like structure on the seafloor to prevent being covered by sand or other debris close to the seafloor. They can have accuracies of up to +/-3mm. While the present solutions are highly accurate, their per-unit cost is prohibitively high. For example, the waverider buoys cost approximately AUD$25,000, which makes them suitable only for point-measurements. In applications where wave height needs to be measured for ship navigation, coastal protection, fishing or even surfing, in most cases, the bathymetry (underwather depth) is relatively uniform. As bathymetry is one of the significant factors that contributes to the nature of the waveform (in addition to prevailing wind, tide, currents, etc.) measuring wave height at a single point would be adequate for the end-user.

However, bathymetry varies substantially in and around areas of a coral reef. This varying bathymetry causes a change in behaviour of the waveform within a narrow spatial range. Thus measuring wave height only at a single point within a coral reef would not yield any useful data. However, the high cost of existing monitoring solutions makes it impossible to carry out wave height monitoring at a high spatial resolution.

This paper describes a technique for measuring the wave characteristics at a high spatial resolution using a densely deployed sensor network. This system would allow scientists to analyse the full 3D characteristics of the waveform as opposed to the 1D measurements that are possible using the existing solutions mentioned above.

Our proposed solution uses wireless sensor nodes equipped with low-power, MEMS-based inertial sensing for determining the wave characteristics such as height and period. By including the time component, the network would also be able to measure parameters such as wave direction and speed. The improvements to the existing waverider buoy system already in operation are as follows:

- Distributed, multiple points of measurements at low cost.
- Fault tolerance through redundancy.
- Improved accuracy and granularity through sensor data fusion.
- Additional information, such as wave speed, three-dimensional water temperature pattern, etc.
- Extensibility and flexibility of ad-hoc network set-up, for further deployments.

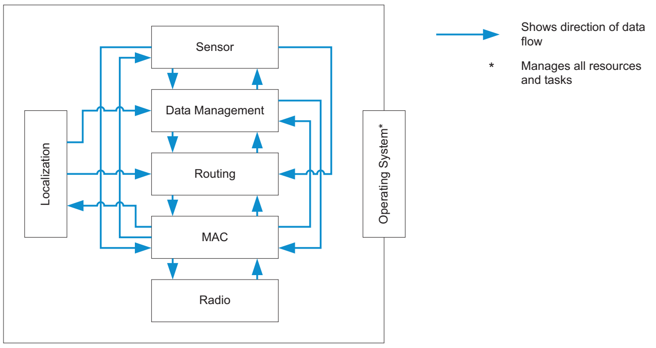

Fig. 1: Data flow within the cross-layered architecture.

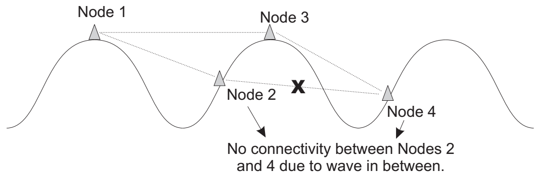

Fig. 2: Example of communication being hindered by wave.

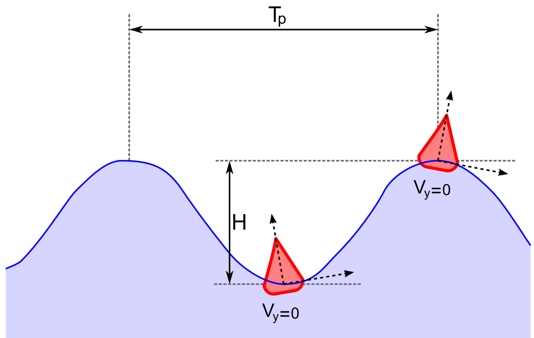

Fig. 3: Wave model and inertial computation diagram.

2. Wireless Sensor Networking

Wireless sensor networks are increasingly being used for environmental monitoring purposes. This is largely due to the fact that densely deployed WSNs allow the environment to be monitored at high spatial and temporal resolutions. Such resolutions are not achievable using present day dataloggers that are generally only used to acquire point-measurements.

However, the fact that WSNs need to operate for extended periods of time but are typically battery operated, means that the various protocols running on the node need to be highly-energy efficient. In conventional computer communication networks, it is common practice to follow the OSI model where every layer in the protocol stack operates completely independently. Thus the operations performed within a particular layer are not dictated by what happens within any other higher or lower layer. While this is beneficial in terms of improving interoperability and modularization, these issues are not of primary concern for WSNs. As an energy-efficient design is of primary concern, WSNs often use a cross-layered approach for protocol design. This approach makes information gathered at a particular layer available to all the other layers. In other words, the main reason for pursuing a cross-layered approach is to maximize information usage.

The advantages of using a cross-layered approach has been discussed in the literature before, e.g. the authors in [6] describe how neighborhood information provided by the MAC layer can be used to adjust the sampling rates of sensors. While this is an example of using information provided by the lower layers to influence the higher layers which deal with data management, in this paper, we propose carrying out optimizations in the opposite direction as well. Thus we intend to use data collected by the sensors to influence the operation of the lower layers which deal with communication. More specifically, the wave height computed by the sensors could help the transceivers decide when communication should take place. Figure 1 provides an overview of our proposed architecture and shows how information is shared between the various layers.

Figure 2 illustrates how the connectivity between neighboring nodes can be affected by wave height. We intend to mitigate this problem by allowing every node to:

1) *Compute wave height*: Details of this step are provided in Section 3.
2) *Deduce correlation patterns*: Nodes will keep track of connectivity information with their immediate neighborhood and also wave height. Local algorithms will then analyze this data to deduce correlations between wave height data and connectivity with every neighboring node.
3) *Use a reliable transport protocol:* Nodes can collaborate by exchanging wave height and connectivity information. This information can subsequently be used to decide which route(s) to take to deliver data reliably to the sink.

3. Wave Structure Analysis

Recent work [11] showed that WSNs can enable a new range of applications by capturing detailed motion parameters from integrated MEMS-based inertial sensors. Building on these experiences, we propose a distributed solution for wave monitoring, using wireless sensor nodes equipped with accelerometers, gyroscopes, and magnetic compasses. Using these sensors, we can measure and compute the following parameters of interest for the wave structure analysis (see also Figure 3):

- *Direction* (D). It is important to sense the direction from where the waves are coming during the peak wave periods. This is achieved by projecting the high amplitude accelerations to the orientation reference information provided by the magnetic compass. The resulting direction is relative to the Earth magnetic North and can be converted to geographic North data by using the latitude-specific declination.
- *Wave height* (H). The height is typically given as the vertical distance between the crest of a wave and the following trough. In addition, the *significant wave height* H_{sig}

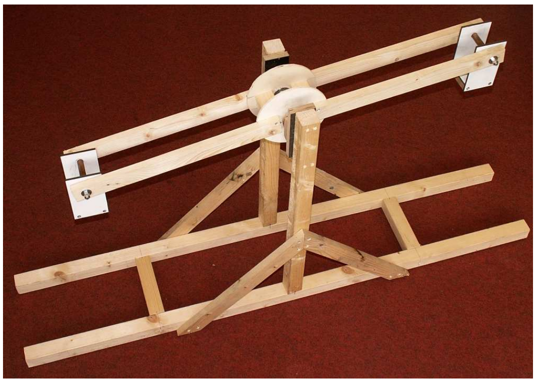

Fig. 4: Wave simulation device.

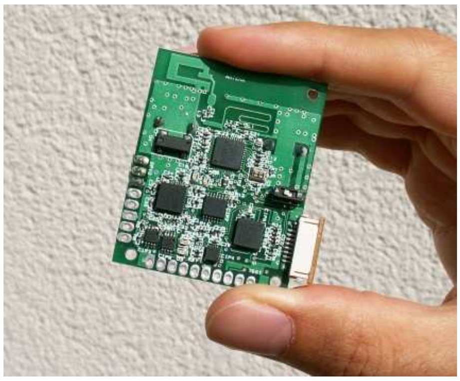

Fig. 5: Prototype inertial sensor board.

is frequently used by meteorologists, oceanographers and coastal engineers. H_{sig} is defined as the average of the highest one third of the waves within a given time frame. This closely approximates the wave height value a person would observe by eye. The accelerometer and gyroscope sensors are used to determine the vertical displacement of the node, and thus measure the wave height.

- *Wave period* (T_p). This represents the time elapsed between two consecutive high-peak waves. The value of T_p indicates whether the waves are generated by local wind fields (sea) or result from distant storms (swell). By analysing the accelerometer data, the wave period can be determined as a the time between two consecutive peaks.
- *Wave velocity* (V). The wave velocity can be determined by measuring the traveling time of the wave peak between two neighboring buoys with sensor nodes (the distance between the two buoys is assumed to be known at deployment time).

A. Laboratory Setup

To evaluate the validity of the wave measurements, we simulate a sea wave using a mechanical laboratory setup. Particles in a wave at sea are generally assumed to show irrotational motion in a circular orbit [5][7]. This means that a buoy floating on the sea surface will make a circular motion in which the bouy itself maintains an approximately upright position in the water. Such motion is very similar to a ride on the Ferris wheel in an amusement park.

For this reason, such a Ferris wheel contraption is also used in practice to evaluate and calibrate the earlier described Waverider [4][17] and other [16] buoys. At sea, the sensor buoys will not maintain a constant attitude, meaning that they will not maintain a level orientation as waves pass by. This is simulated in one dimension by the Ferris wheel, since its gondolas on which the wave sensors are mounted can pivot in one direction around their mounting points on the wheel. We employ the Ferris wheel simulation stategy at a relatively small scale with a beam wheel diameter of about one meter. Our version of the Ferris wheel wave simulator is shown in Figure 4.

Figure 5 shows the prototype inertial sensor board we use in our experiments. The board features a three-axial accelerometer, a two-axial gyroscope and a three-axial digital compass [13]. The inertial sensors are sampled through a low-power MSP430 microcontroller [12], which communicates the data wirelessly through the IEEE 802.15.4-compatible CC2430 radior [10]. In our laboratory setup, the board is fixed rigidly into the small gondolas attached at the edges of the Ferris wheel. The diameter of the wheel, corresponding to the simulated wave height, is approximately 100cm.

B. Sensor Calibration

In order to obtain correct and reliable measurements, the sensors on the nodes need to be calibrated. The gyroscope is rougly factory-calibrated and we use its measurements without further calibration. The accelerometer does need to be calibrated however.

A triaxial accelerometer, like the one we use, measures acceleration as a three-dimensional vector expressed in three separate axis values a_x, a_y and a_z. Unfortunately, the accelerometer is not equally sensitive on all axes and a zero acceleration does not necessarily yield a zero sensor output. These two effects respectively mean that the indiviual axis sensors can have different scale s and nonzero offset o values. Additionally, the axes of the sensor will not be fully ortogonal. This means that even when the sensor is moved in the exact direction of of one of the axes, it can still present a signal on the other two axes. This is commonly called the misalignment error or cross-axis influence.

To obtain the true acceleration measurement, these calibration parameters need to be determined. We use a simple, yet effective calibration strategy that does not require an intricate contraption to subject the sensor to well-defined accelerations in will-defined directions. In stead, we make clever use of the constant force of gravity. Very similar versions of this method are described in various recent publications [8][9][14][15].

The central idea of this method is that the accelerometer will measure only the gravitational acceleration when it is stationary. Measuring this constant acceleration at equally distributed stationary sensor orientations provides enough information to calibrate the sensor for scale, offset and cross-axis influence.

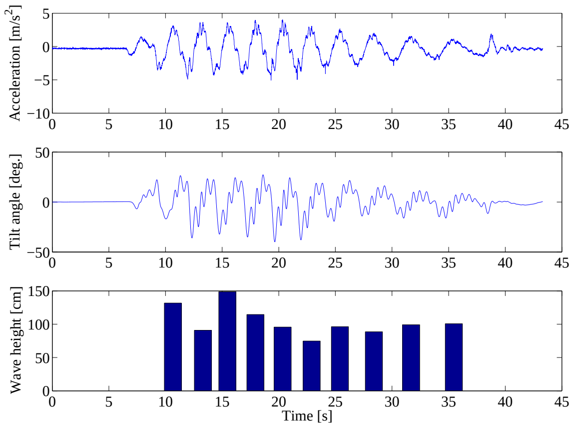

Fig. 6: Vertical acceleration, tilt angle integrated from the gyroscope readings, and wave heights computed during a typical experiment.

In practice, this means that the sensor is placed in a series of discrete orientations while recording the sensor output in each situation. The desired calibration parameters are determined from the obtained sensor measurements by solving a non-linear Least Squares (LS) problem. This problem describes that for all obtained measurements the magnitude of the calibrated acceleration measurements must equal a constant gravitational acceleration. For the tests described in this paper we only calibrated for scale and offset parameters.

C. Wave Measurements

Of the wave parameters described at the beginning of this section we currently only measure and compute the wave height and the wave period. The accelerometer is used to determine the vertical displacement of the sensor. Because the sensor itself will float with a continouosly changing attitude, a gyroscope is used in order to compute the real vertical acceleration relative to the Earth plane, i.e. along the orientation of the gravity vector g. This projected acceleration is subsequenty integrated twice to obtain an estimate of the vertical displacement of the sensor, i.e. the wave height. Wave peaks are detected using the accelerometer alone. This peak information can be used for determining the wave period, but it is also used to reset the acceleration integration process periodically.

1) Wave period: To compute the real vertical acceleration relative to the Earth plane, current tilt angles of the sensor are needed. The tilt angles are computed by integrating the angular rate reported by the gyroscope and this gives the inclination of the sensor body frame relative to the Earth reference frame. Using the inclination information, we can project the sensed accelerations on the Earth vertical axis, which is shown in the top graph of Figure 6 (the results in the graph compensate for the gravity vector g). We can observe clearly the wave peaks in the acceleration readings and, consequently, derive the wave period T_p by measuring the time between consecutive peaks.

2) Wave height: The wave height H is measured by double integration of the projected vertical acceleration. In order to limit the effect of error accumulation, the velocity on the vertical axis is reset to zero at the wave peaks. In other words, the wave height is computed between the rising and falling edges of the wave. In our experimental setting, this corresponds to measuring the diameter of spinning wheel. In the current experiments, the error accumulation in the integration of the gyroscope angular rate is not compensated, meaning that the performance of the whole system can diminish as time passes.

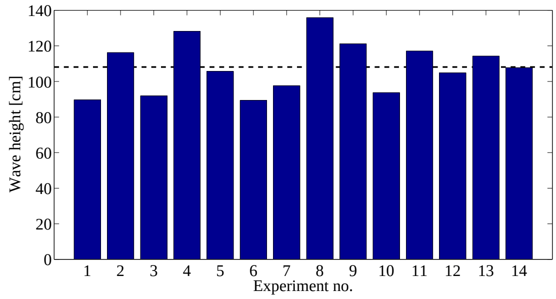

Fig. 7: Overall results of wave height measurements.

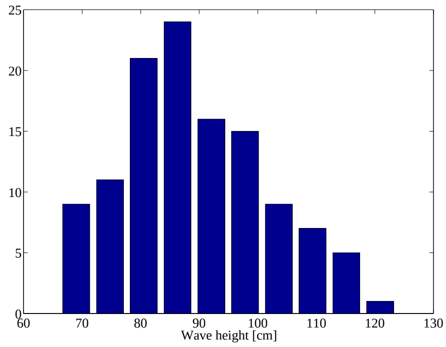

Fig. 8: Histogram of wave heights during a long experiment.

4. Results

In this section we present the results of measuring the wave height H, which is the most challenging task due to the inherent inertial sensor noise and error accumulation through double integration of acceleration.

A. Laboratory Setup

We start with initial experiments using the wave simulation device presented in Section 3-A. Figure 6 depicts the behavior of the system during one typical experiment. Figure 7 cumulates the results of a series of 14 similar experiments in which we simulated a total of approximately 400 waves of different periods. These results show the average height obtained in each experiment. The overall average wave height measured by the system is 108cm (standard deviation 14.7cm), compared to the real diameter of the spinning wheel of 100cm.

We also perform an experiment with a much longer duration, consisting of approximately 130 waves. In such a

Fig. 9: Ferris wheel used for official test by Datawell BV.

long experiment we can expect more significant errors due to error integration in the gyroscope angular rate. The average wave height obtained is 90cm (10cm below the correct value). Figure 8 shows the histogram of wave heights measured on a moving average during this experiment.

B. Datawell Ferris Wheel

For more comprehensive tests, we evaluate our system using the Ferris wheel developed by Datawell BV [1] at their manufacturing site in Heerhugowaard, the Netherlands. The Ferris wheel is presented in Figure 9. It accommodates a Waverider buoy, on top of which we attach our inertials sensor platform. The wheel starts from an equilibrium position and rotates at a controllable rate, which would correspond to the wave period. The simulated wave height (i.e. the real vertical displacement of the buoy) is 180cm.

Figure 10 presents the results of our test using a rotation period of 12.5s. The average wave height is 165cm (15cm below the correct value), with a standard deviation of 34cm. The histogram indicates an outlier at 80cm.

The accuracy improves significantly in the tests with a rotation period of 5s shown in Figure 11. The average wave height is exactly 180cm, with a standard deviation of 26cm. The histogram is also balanced, with a clear peak at the correct value. This difference in accuracy is due to the higher accelerations applied in the second case. Since the accelerometer is set at the same sensitivity range in all tests, the effect of noise is considerably smaller when measuring and integrating higher acceleration values.

5. Conclusions

Wave structure analysis is required for short and long term investigations of environmental dynamics of highly complex marine systems such as the Great Barrier Reef (GBR). In order to better understand the complexities and predict the change in dynamics accurately, it is essential to have a monitoring system that is capable of capturing information at a high spatial resolution.

In this paper, we propose a solution for wave monitoring based on WSNs. Using this technology, various wave parameters can be monitored, such as height, direction, speed and

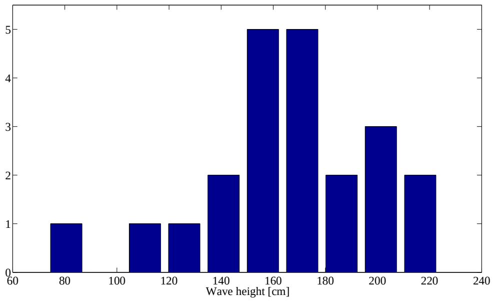

Fig. 10: Histogram of wave heights during experiments with the Ferris wheel of Datawell BV. The period of rotation is set at 12.5s.

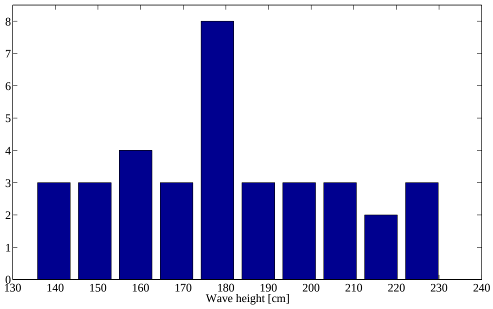

Fig. 11: Histogram of wave heights during experiments with the Ferris wheel of Datawell BV. The period of rotation is set at 5s.

period. Our solution captures detailed motion parameters from integrated MEMS-based inertial sensors, such as accelerometers and gyroscopes.

We conduct laboratory experiments using a Ferris wheel contraption, which is a technique used in practice to evaluate and calibrate wave monitoring solutions. The experimental results show an accuracy of approximately 10cm for a wheel diameter of 100cm. We also evaluate our system using the Ferris wheel developed by Datawell BV for testing commercial Waverider buoys. The results indicate that the accuracy depends on the amplitude of acceleration incurred by the sensor, ranging on average from 0 to 15cm, for a simulated wave height of 180cm.

For future work, we plan to increase the accuracy of the system by applying real-time compensation of gyroscope error accumulation and by fusing data from multiple sensor nodes. We also plan a series of deployments in GBR (initially in Nelly Bay, which is easily accessible, and later on in Davies Reef) and thus analyze the system performance and robustness in a real-life setting.

Acknowledgements. We would like to thank Datawell BV for facilitating our tests at their site. This work was partially funded by the Dutch projects Featherlight and Smart Surroundings and by the EU project SENSEI, “Integrating the Physical with the Digital World of the Network of the Future” (www.sensei-project.eu), contract number: 215923.

REFERENCES

[1] Datawell oceanographic instruments. http://www.datawell.nl.

[2] Falmouth scientific, Inc. http://www.falmouth.com.

[3] Queensland environmental protection agency. http://www.epa.qld.gov.au.

[4] SF Barstow, HE Krogstad, K. Torsethaugen, and T. Audunson. Procedures and Problems Associated with the Calibration of Wave Sensors. *Evaluation, Comparison and Calibration of Oceanographic Instruments*, 1985.

[5] P. Boccotti. *Wave Mechanics for Ocean Engineering*. Elsevier Science, 2000.

[6] Supriyo Chatterjea. *Distributed and Self-Organizing Data Management Strategies for Wireless Sensor Networks: A Cross-Layered Approach*. PhD thesis, University of Twente, The Netherlands, 2008.

[7] R.G. Dean and R.A. Dalrymple. *Water Wave Mechanics for Engineers and Scientists*. World Scientific, 1991.

[8] W T Fong, S K Ong, and A Y C Nee. Methods for in-field user calibration of an inertial measurement unit without external equipment. *Measurement Science and Technology*, 19(8):085202 (11pp), 2008.

[9] I. Frosio, S. Stuani, and N.A. Borghese. Autocalibration of mems accelerometer. *Instrumentation and Measurement Technology Conference, 2006. IMTC 2006. Proceedings of the IEEE*, pages 519–523, April 2006.

[10] Texas Instruments. CC2430 System-on-Chip Solution for 2.4 GHz IEEE 802.15.4 / ZigBee. http://focus.ti.com/docs/prod/folders/print/cc2430.html.

[11] R. Marin-Perianu, M. Marin-Perianu, P. Havinga, and J. Scholten. Movement-based group awareness with wireless sensor networks. In *Pervasive*, pages 298–315, 2007.

[12] MSP430 family of ultra-low-power microcontrollers. http://focus.ti.com/docs/prod/folders/print/msp430f1611.html.

[13] ProMove inertial measurement unit. http://www.prosyspc.ro.

[14] Isaac Skog and Peter Händel. Calibration of a mems inertial measurement unit. *17th IMEKO World Congress, September 2006, Rio de Janeiro, Brazil*, 2006.

[15] Z F Syed, P Aggarwal, C Goodall, X Niu, and N El-Sheimy. A new multi-position calibration method for mems inertial navigation systems. *Measurement Science and Technology*, 18(7):1897–1907, 2007.

[16] W. Tardivel, A. Parker, and A. Baird. The development of a new u.k. wave height measuring buoy. *OCEANS*, 12:74–79, Sep 1980.

[17] J. Wilson and J. Taylor. Experiences With Waverider Buoys In The Canadian Wave Climate Study. *OCEANS*, 15, 1983.